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Test Procedure

Donner Model 4310
Accelerometer

October, 1962

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THEORY OF OPERATION

Donner Model 4310

Forced Balance Accelerometer

October, 1962

THEORY OF OPERATION

The Donner Model 4310 is a pendulous servo force-balance accelerometer. The basic principle underlying the operation is depicted in Figure 1. In this system the seismic mass is free to pivot about the torque coil axis and its displacement is measured with an inductive type pick-off coil. The output voltage from this position transducer is amplified with a high gain amplifier whose output is a current. The current flows through a torque coil which forces the mass back to its original null position. The torque coil current, necessary to zero the position of the mass, is proportional to acceleration and is measured as a voltage across a resistor in series with the torque coil. For the types of instruments employing electrical damping it is possible to obtain high damping that is independent of temperature with appropriate equalization of the servo.

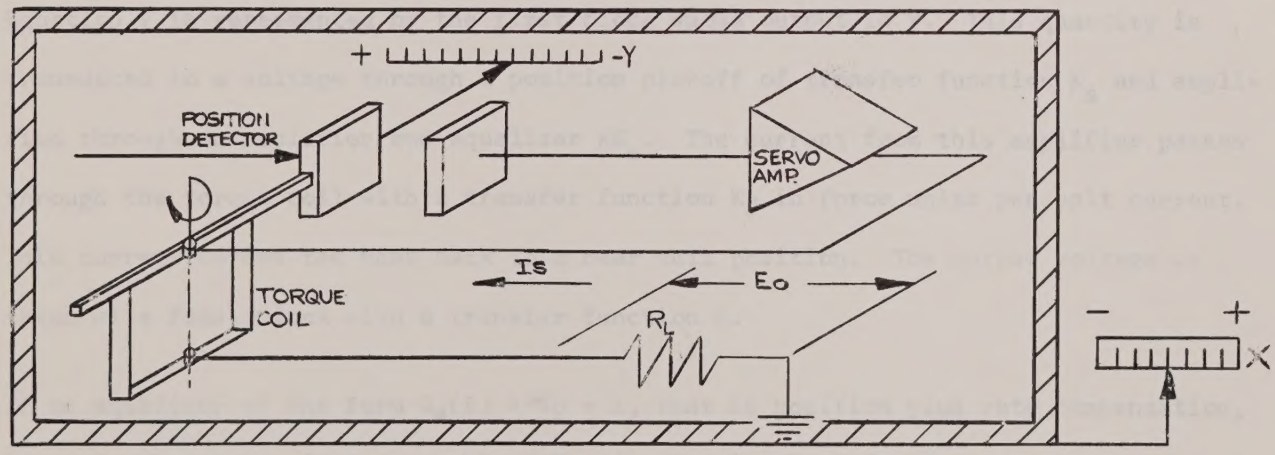

FIG. 1

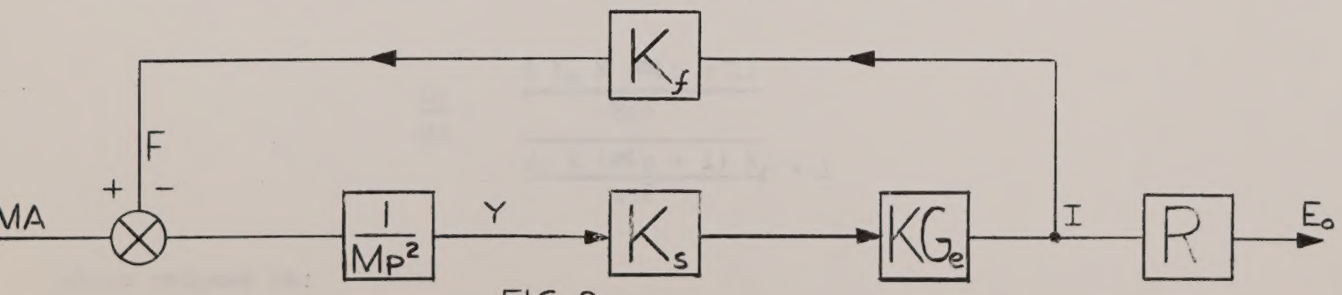

FIG. 2

THEORY OF OPERATION

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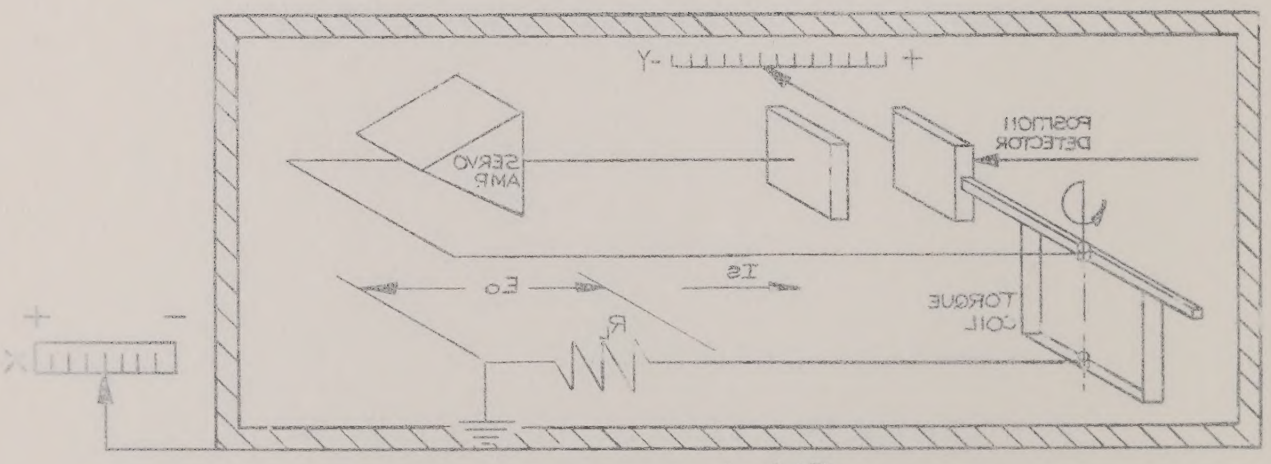


FIG. 1

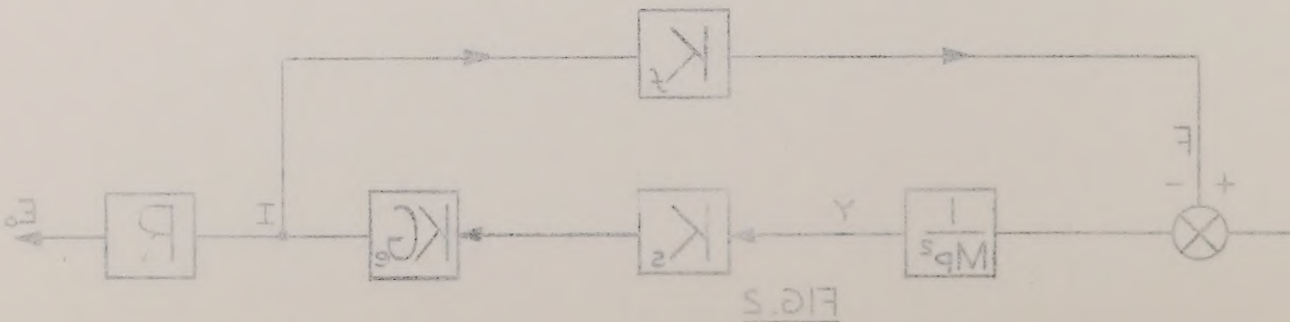


FIG. 2

The analysis of the force balance accelerometer shown in Figure 1 is based upon the block diagram of Figure 2. If the seismic mass is free to pivot about the torque coil axis with essentially zero damping, the force on the mass is related to the displacement as follows:

1.) $F=Mp^2 (Y - X)$

The above is based on the fact that the motion of the mass in inertial space is the difference between the Y and X movements. Also, there is no restoring spring such as in an open loop device. It should be noted that even though the Y displacement is an arc, its movement is so slight that, for discussion purposes, it is considered linear.

The above equation can be rewritten as:

2.) $Y= \frac{1}{Mp^2} (F + Mp^2 X) = \frac{1}{Mp^2} (F + MA)$

p is the Laplace transform operator, and zero initial conditions are assumed. Equation 2 is represented by the first block whose output is Y. This quantity is transduced to a voltage through a position pickoff of transfer function K_s and amplified through an amplifier and equalizer KG_e. The current from this amplifier passes through the torque coil with a transfer function K_f in force units per unit current. This current forces the mass back to a near null position. The output voltage is taken at a final block with a transfer function R.

If an equalizer of the form $G_e(P) = \alpha p + 1$, that is position plus rate compensation, is used, the system is made stable. The damping is electrically controllable (as is varied), so is independent of temperature effects. α is a time constant and is derived from an RC network. The closed loop system has the equation:

$$\frac{Eo}{MA} = \frac{\frac{R K_s K (\alpha p + 1)}{Mp^2}}{\frac{K_s K (\alpha p + 1) K_f}{Mp^2} + 1}$$

which reduces to:

$$\frac{Eo}{A} = \frac{R\,K_s\,K\,(\alpha p + 1)}{p^2 + (K_s\,K\,\alpha\,K_f/M)\,p + K_s\,K\,K_f/M}$$

where

$$w_n^2 = \frac{K_s\,K\,K_f}{M}$$

$$\zeta = \frac{\alpha}{2}\sqrt{\frac{K_s\,K_f\,K}{M}}$$

The closed loop force balance accelerometer transfer function becomes:

$$\frac{Eo}{A} = \frac{R\,K_s\,K\,(\alpha p + 1)}{p^2 + 2\zeta w_n\,p + w_n^2}$$

Besides a controlled damping the resonant frequency is proportional to the square root of the loop gain and consequently high resonant frequencies are possible.

The use of an electrical force rather than a mechanical force such as a spring or taut wire, eliminates many of the non-linearities and drift problems encountered with the latter system.

In the case of oil damping, the moving system is immersed in silicone oil and consequently damping and natural frequency are a function of oil viscosity. However, by using electrical damping in conjunction with oil damping some of the shortcomings of oil damping can be overcome.

TEST PROCEDURES

In order that the user may check against the specification to which he has purchased his Donner Model 4310 Accelerometer we are presenting a description of the more important Quality Assurance tests utilized by us.

We recommend that if a complete test of the instrument performance is to be made that the sequence of tests presented below be followed.

Where applicable full range voltage is defined as full excursion between maximum negative and maximum positive values. Full-scale voltage is defined as full output of one polarity (normally half full-range).

1. Pivot Flop.

   This test is utilized to determine whether there is any lateral movement of the pivot in the jewel housing. With the output of the accelerometer connected to an oscilloscope (suggested sensitivity 100 mv/cm), produce a full-range output voltage for instruments up to 10 G range by taking the instrument in hand moving it back and forth along its sensitive axis. The sinusoidal waveform observed on the oscilloscope should contain no sharp transients which would indicate pivot flop. (For instruments of larger range a 10 G input is sufficient for this test).

2. Sensitive Axis Alignment.

   This test is to determine the degree of alignment of the sensitive axis with respect to the bottom and side of the case.

The following mechanical items are needed:

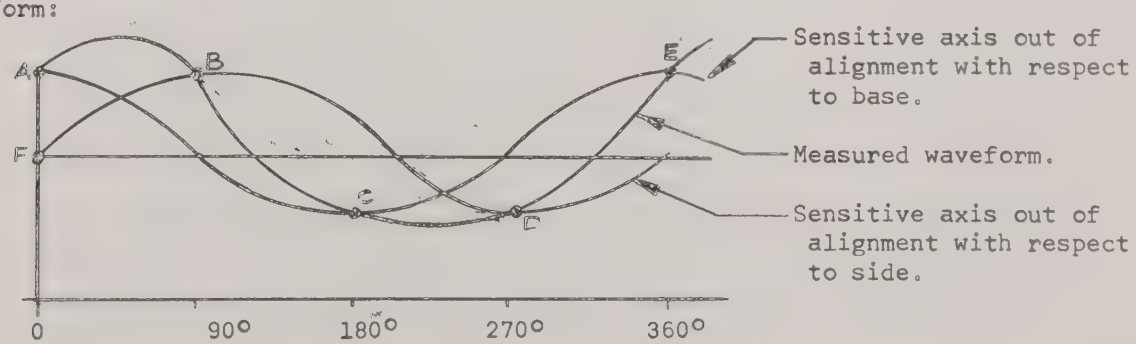
1. Precision rotary table.

2. Precision 4" square block with two tapped holes 2" from the side for 6/32 screws for mounting the accelerometer. The sides should be parallel and perpendicular to 1.5 minutes of arc.

3. Starret precision level with an accuracy of better than 1.5 minutes of arc.

4. Two 1-1/4" gauge blocks.

Referring to Figure 1, mount the precision block on the face of the rotary table. Then, utilizing the Starret Level, rotate the rotary table so that the top surface is perfectly horizontal. Next, using the gauge block, secure the accelerometer to the horizontal surface with #6/32 machine screws so that the long side is perfectly parallel to a side of the precision block perpendicular to the horizontal surface. When the accelerometer is properly secured to the block apply the power and read the output with a null voltmeter and at the same time tap the instrument to remove turn-on stiction. Next rotate the table 4 times in 90° increments, and record the output at each position. The values recorded will be four points on a sine wave and will have the following form:



The sensitive axis misalignment with respect to the base can be determined from 1/2 (A-C) and the sensitive axis misalignment with respect to the side of the case can be determined from 1/2 (B-D). The voltage output which is determined by Point F, 1/2 (A+C) or 1/2 (B+D), is the combined

output due to spring-offset stiction, and the 2.5 volt bias voltage output (telemetry models only).

An important thing to be noted in the above test is that once the readings have been started, the table should not be tapped or jarred. If the table were tapped, the readings would then include the error due to bearing stiction which should be measured separately. These values read during this test can be converted into degrees by using the volts-per-G calibration of the accelerometer.

3. Voltage Calibration (Volts/g)

3.1 If instrument range is 1 G or greater:

A. Stand the accelerometer on one end on a level surface to produce an output voltage equal to 1 G (arrow pointing down produces a negative output).

B. Measure the output voltage on a differential voltmeter to the nearest millivolt (or specified accuracy). When the output voltage to be measured is 1.6000 volts or less, and an accuracy of 0.05% or better is required, use a universal potentiometer to measure the voltage.

C. Reverse measuring instrument input polarity for standard units and stand the accelerometer on its opposite end to reverse acceleration to 1 G of opposite polarity. In the case of a telemetry unit the two values will be symmetrical about the +2.5 volt bias.

D. For a standard unit, take the average of the +1 G and -1 G readings to compute volts-per-G calibration. For a telemetry unit, take one-half of the difference between the two readings to compute calibration in volts-per-G.

3.2 If instrument range is less than 1 G:

A. Mount the accelerometer on the horizontally level surface of the precision 4" square block fastened to the vertical face of the rotary table.

Orient the accelerometer so that its sensitive axis is perpendicular to the axis of rotation of the rotary table. Connect the accelerometer to the power supply and tap the instrument to remove turn-on stiction. Rotate the rotary table to produce zero volts output (or 2.5000 volts for telemetry) from the accelerometer. Note the angular setting then rotate the table 180° and note output reading. Re-set the table so as to produce an output voltage equal to zero (or 2.500) + 1/2 the voltage change observed for the 180° rotation. For example, the table was rotated to produce an output of 2.500 volts. Rotating the table 180° produced an output of 2.560 volts. Rotate the table back to original 2.500 volt output position and adjust the table to produce 2.530 volts. Consider this your reference point.

B. Rotate the table to the positive angle whose sine is equal to the full-scale G input of the accelerometer, and read the output voltage to the nearest millivolt. (Example: for a 0.5 G range instrument, rotate table to 30°, the sine of which is 0.5).

C. Rotate the table to an equal negative angle and note voltage.

D. Record the average of these readings as full-scale voltage.

4. Temperature Calibration.

4.1 For 1 G and higher ranges:

A. Fasten the accelerometer to a precision angle table within a Delta Model 6545L or equal test chamber using a 90° block so that the sensitive axis is parallel to the plane of rotation and directed vertically upwards when viewed from the face of the rotary table, (i.e., at +1 G input).

B. Rotate the rotary table until the base of the accelerometer is vertical as determined by a spirit level. Measure the output voltage at +1 G orientation. Rotate the rotary table 180° so that the accelerometer is oriented to -1 G. Record the output

voltage again.

C. Cool the test chamber to -40°F (or the lowest temperature specified). Allow 30 minutes for thermal stabilization within the instrument. Measure and record the -1 G and +1 G voltage readings.

D. Heat the test chamber to 212°F, allow 30 minutes for thermal stabilization, and repeat the +1 G and -1 G measurement.

E. Cool the test chamber to room temperature again (to the same temperature at which the readings in Step B were taken), allow 30 minutes for stabilization and repeat the voltage measurements.

F. Calculate the maximum variation per degrees F over the entire range, using the following formula:

$$X = 100A/BC$$

where X = % change /°F

A = maximum V/G - minimum V/G

B = average of the four readings

C = total temperature span of the test, e.g., -40 to +212°F

The value of X should not exceed .01%/°F for standard instruments. For instruments that have been ordered with special temperature compensation the temperature extreme should not exceed plus or minus 25°F about ambient.

5. Bearing Stiction.

5.1 Tapping Method:

A. Place the accelerometer base down on a level surface.

B. Tap the table sharply and note that a new value of output voltage may be read. This phenomenom may be observed when the accelerometer is in any position. The difference in reading should not exceed 1 microampere X the accelerometer load resistance for standard instruments and .11% of full-scale voltage for telemetry instruments.

5.2 Turn-on Stiction:

A. With the accelerometer base down on a level surface observe the output voltage reading.

B. Turn the power supply off and then turn it on again. The reading may change but the difference in readings should not exceed 5 micro-amperes X the load resistance for standard units and .55% of full-scale for telemetry instruments. The output should return to normal (within the limits of Paragraph 5.1) when the table is tapped.

6. Pull-in Time.

A. Lay the accelerometer on a level surface in the 0 G position (base down) for instruments of less than 1 G and in the +1 G position (end down) for instruments of 1 G or greater range.

B. Connect an oscilloscope across the output terminals and adjust the scope to observe the output using an internal sweep time base of 100 Milliseconds/cm. For fluid damped instruments use a 5-second sweep time.

C. Short the torque coil, for standard instruments, pins 3 and 4, for approximately 15 seconds to cause a saturated output and then break the connection. Note the length of time required for the output voltage to return to approximately 63% of the final value.

7. Transient Response Test (For Air-Damped Instruments Only)

A. Use test circuit shown in Figure 5 or 5T.

B. Adjust the oscilloscope, using a suggested time base of 10 milliseconds/cm. Adjust the vertical gain so that a 10 cm (one division) deflection is observed when the transient response button is pressed and released. Determine the percentage of overshoot when the button is released as defined in Figure 7. Refer to Figure 8 to read the damping ratio from the graph and record it.

8. Frequency Response (For Air-Damped Instruments Only)

A. The test circuit is shown in Figure 11.

B. Place the accelerometer on a level surface.

C. Connect the signal generator lead to the horizontal input of the oscilloscope.

D. Apply a 10 cps, 10 volt output signal from the oscillator and adjust the oscilloscope and the oscillator amplitude controls until a trace appears on the oscilloscope of convenient vertical and horizontal amplitude. It is suggested to set both amplitudes for 10 cm deflection (full excursion).

E. Increase the frequency of the oscillator and at the same time adjust the oscillator output amplitude as necessary to maintain a constant horizontal amplitude of trace on the oscilloscope.

F. Record the frequency at which vertical amplitude of trace is maximum and the value of the peak.

G. While still maintaining a constant amplitude of horizontal trace, increase (or decrease, as necessary) the oscillator frequency until a pattern appears on the oscilloscope indicating a 90° phase relationship between the vertical and horizontal input signals. (If vertical and horizontal deflections are equal, the pattern will be a circle; if not equal, the pattern will be an ellipse with vertical and horizontal axis). Record this natural resonant frequency (F_N) and the vertical amplitude.

9. Frequency Response (Fluid-Damped Instruments)

A. Use test circuit shown in Figure 6.

B. Place the accelerometer with base horizontal on a shaker table with the sensitive axis parallel to the direction of vibration.

C. Connect the output of the accelerometer to the vertical input of the oscilloscope.

D. Connect the horizontal input of the oscilloscope to the velocity pickoff coil on the shaker table. Turn on power and apply a 10 cps (unless

otherwise specified) low-amplitude vibration (not exceeding 50% of the full scale G of the accelerometer nor too low for usable signal-to-noise ratio) as indicated by the oscilloscope.

E. Increase the frequency of vibration until the oscilloscope trace appears as a slanting straight line and record this as the natural frequency reading, F_n.

F. Adjust the oscilloscope so that a large pattern occurs on the screen, lower frequency until pattern shown in Figure 9 (for 30°) is obtained and record as $F_{30°}$.

G. Refer to Figure 9 to determine damping ratio from F_n and $F_{30°}$ and record value of damping ratio.

H. When desired, refer to Figure 10 to determine the frequency F_x where the output amplitude is down by 5%, or as otherwise specified.

10. Noise.

A. Place the accelerometer on a level platform which is insulated against minute vibrations.

B. Connect an AC vacuum tube voltmeter across the accelerometer output terminals.

C. Read AC output voltage to the nearest 0.1 millivolt RMS while the accelerometer is in this position. AC noise level must not exceed the amount specified for the instrument. (Standard specification is 0.05% of full-range voltage.)

D. Vary total supply voltage $\pm$ 15%. Noise should not exceed 0.05% of full scale at any supply voltage.

11. Hysteresis and Linearity.

Note: The following tests are performed using the current torque method. Since the Donner Model 4310 Accelerometer contains a precision servo loop, a good deal of useful and precision information on its performance can be obtained by injecting precisely known disturbances and monitoring the error in the servo loop. In order to accurately determine the value

of the injected disturbance, the output of the instrument under test should be monitored. In the particular case described below a known disturbance in the form of a current representing a specific G level is compared with the error current. The set-up is shown in Figure 12.

The signal generator is hooked up with a 2.4 K and 1 K load in series with the torque coil and the output is read as voltage drop across the 1 K resistor. During this test the accelerometer is located on a level surface which is isolated from possible recorder vibration. Since it is in a zero G field, there can be no net current flowing in the torque coil when the instrument is in servo. Since a current is being injected equal to full scale, or a portion thereof, then an equal and opposite current must flow out of the amplifier to balance out the injected current and produce a net current of zero in the torque coil. Since the current flowing from the servo amplifier can never be exactly equal to the injected current, unless the amplifier had infinite gain, the difference in current measured across the 2.4 K resistor is the error current.

If the voltage drop across the 2.4 K resistor is plotted against the voltage drop across the 1 K resistor, a hysteresis loop is obtained, some examples of which are shown in Table 1 and Figure 13. In addition to determining the hysteresis and linearity as explained in the following procedure, the hysteresis loop also provides valuable information on the operation of the servo loop.

11.1 Current-Torque Method.

Caution: When injecting a current from the signal generator, precaution should should be taken not to exceed 5 milliamps of current. Otherwise, the torque coil may be permanently damaged.

Hysteresis is recorded by an X-Y recorder which plots input current versus error current. When cross-axis sensitivity by the current torque method is also required, perform these two tests together (See 12).

A. The test circuit is shown in Figure 12 and 12 T.

B. Place the accelerometer base down on a level platform.

C. Adjust the recorder X input for sensitivity of 2.5 microamperes per inch (50 mv range) for error output current reading. For fluid-damped instruments of large damping ratio, it will be necessary to use the 500 mv range. Adjust the Y input for a sensitivity of 1 milliamp per inch (10 v range) for input current reading.

D. When testing air-damped instruments, set the signal generator for 0.02 cps. When testing fluid-damped instruments, set the signal generator for 0.01 cps.

E. Adjust the signal generator output amplitude for full excursion thru 1 cycle of input voltage of at least 3.0 inches on the Y axis, corresponding to 3.0 milliamperes of drive current for standard instruments. (Refer to instrument calibration record for full-range current data.)

F. Start the recording (Figure 13 shows a sample recording of a hysteresis loop). During normal testing procedure, measurements are not required for the loop, but its general appearance should closely resemble the sample recording and the maximum width of the loop should not exceed approximately 1.3 inches, or 3.2 microamperes error current peak-to-peak.

G. When hysteresis measurements are required, use the X plot of the X-Y recorder to calculate the hysteresis as a percentage of full-range voltage as shown by the example in Figure 13.

H. Calculate the non-linearity as illustrated in Figure 14.

12. Cross-Axis Sensitivity (Current Torque Method).

A. Follow Steps A through F of the hysteresis test (11.1), except place the accelerometer on its side with the arrow on the cover pointing toward the observer's left. Allow the X-Y recorder to trace a loop on the left side of the graph paper. Lift the pen when the loop has been completed.

B. Place the accelerometer on its opposite side and trace a second loop at the right-hand portion of the graph paper. Do not adjust the drum positioning knob.

C. Draw lines connecting the end points of each loop and calculate cross-axis sensitivity as shown in Figure 13. Record this value.

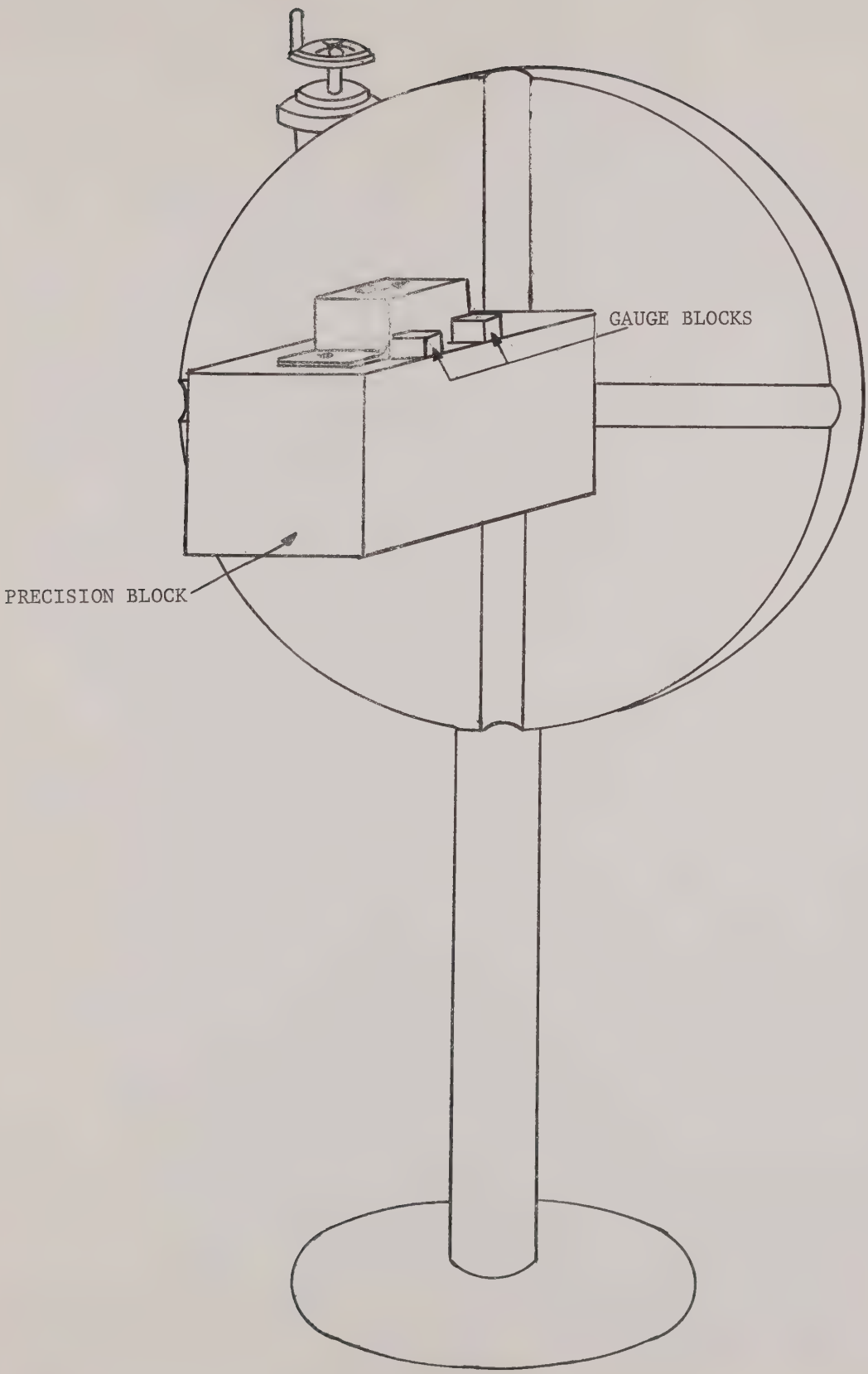


FIGURE 1

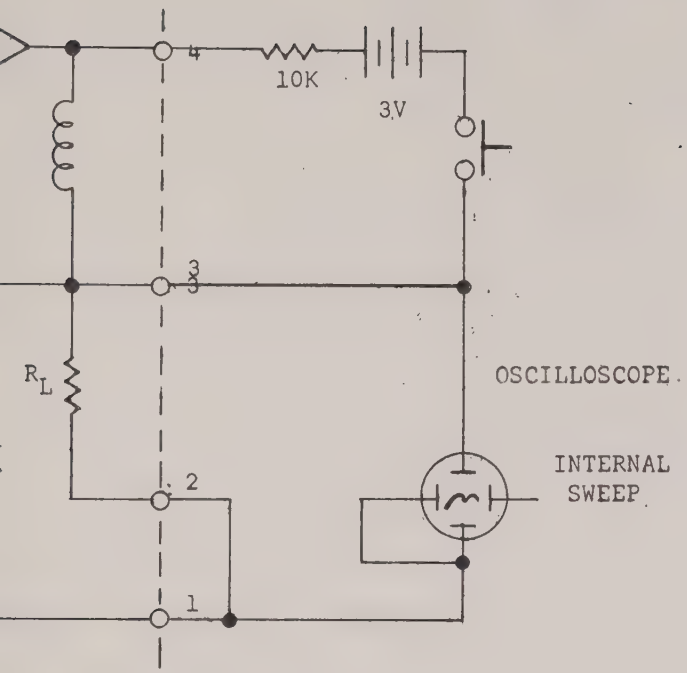


FIGURE 5
Transient Response
TEST CIRCUIT

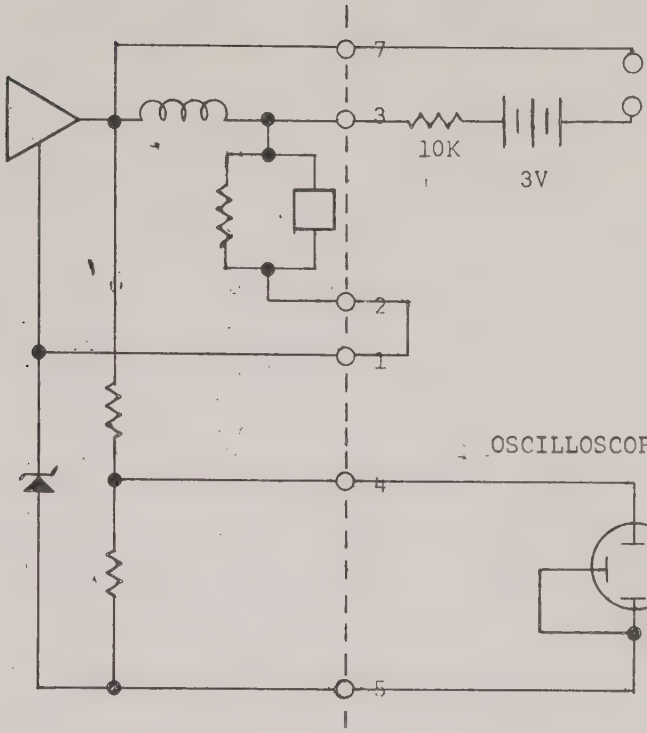


FIGURE 5 T (Telemetry)
Transient Response
TEST CIRCUIT

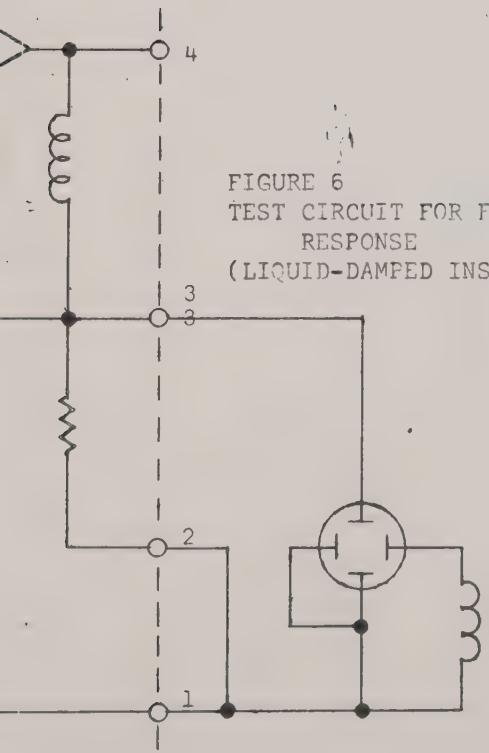


FIGURE 6
TEST CIRCUIT FOR FREQUENCY
RESPONSE
(LIQUID-DAMPED INSTRUMENT)

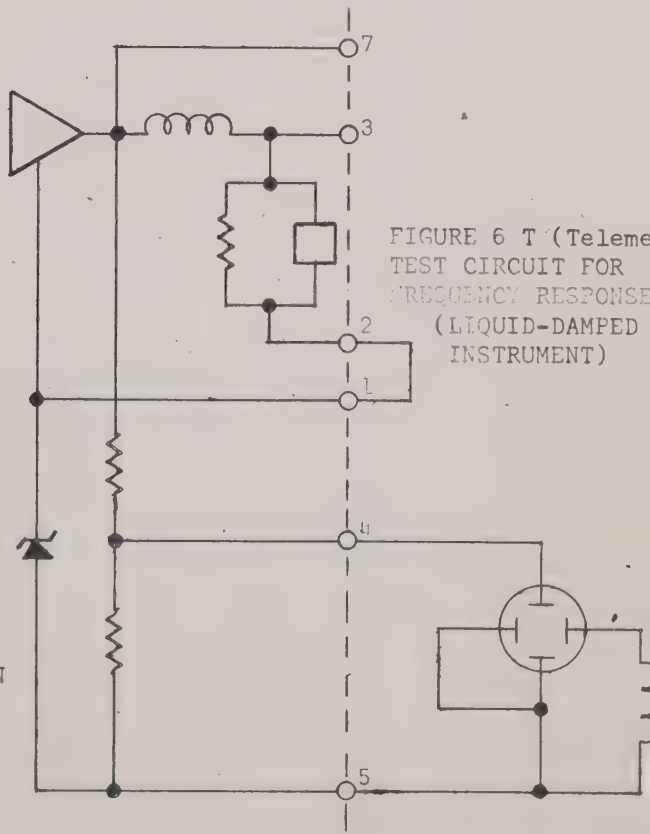


FIGURE 6 T (Teleme
TEST CIRCUIT FOR
FREQUENCY RESPONSE
(LIQUID-DAMPED
INSTRUMENT)

PICKOFF COIL ON
SHAKER TABLE

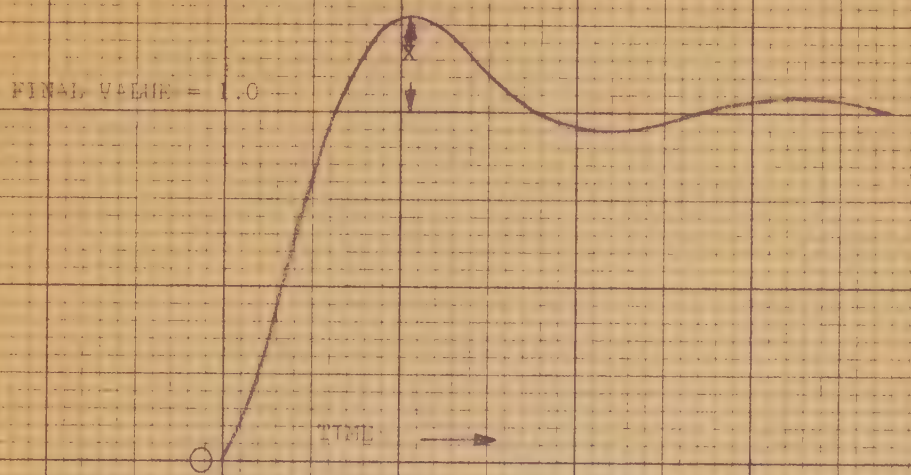


FIGURE 7 - HEIGHT OF OVERSHOOT OF A RESPONSE TO A STEP INPUT

1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
1.0
.5
.4
.2
0

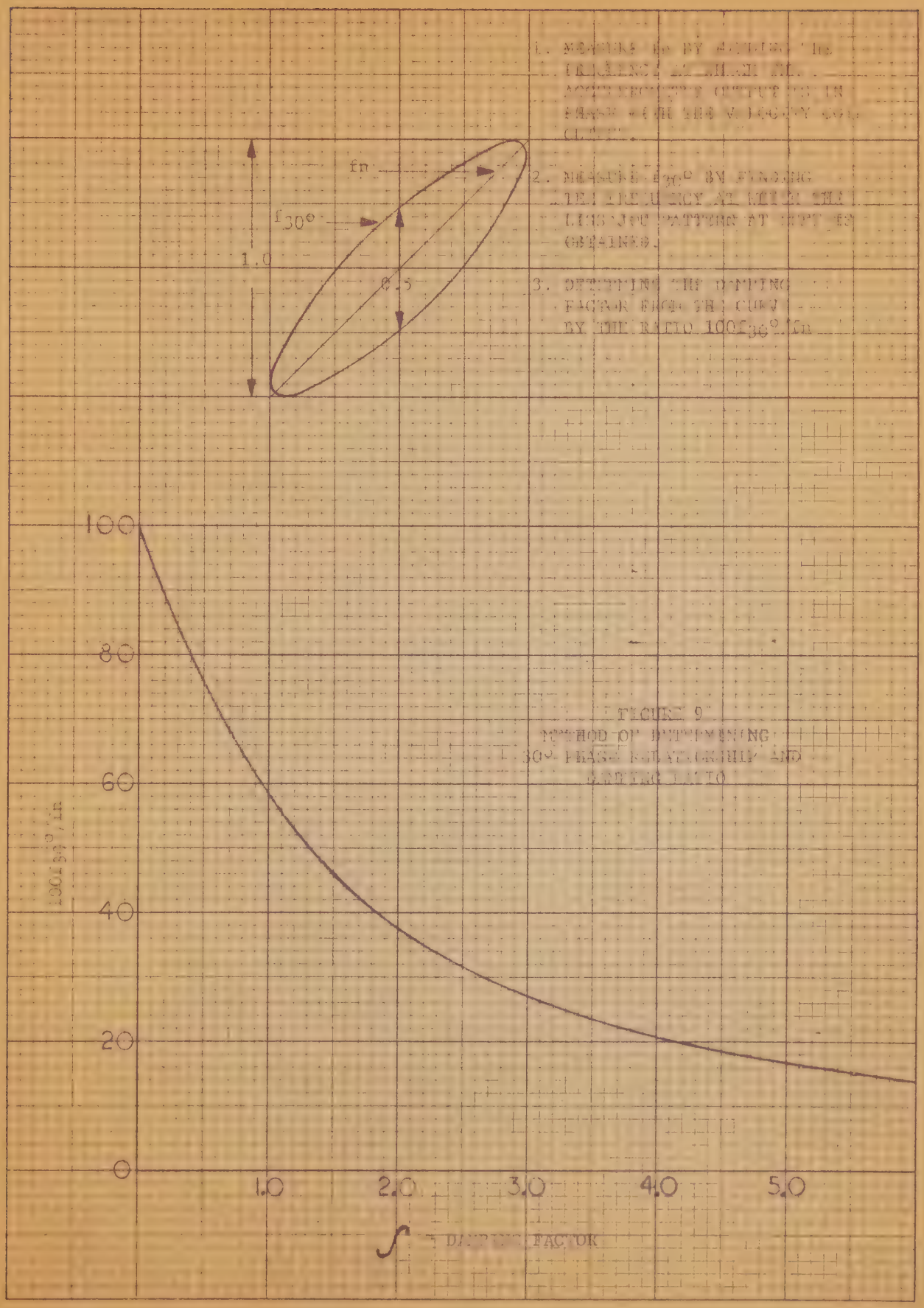


FIGURE 9
METHOD OF DETERMINING 30° PHASE RELATIONSHIP AND DAMPING RATIO

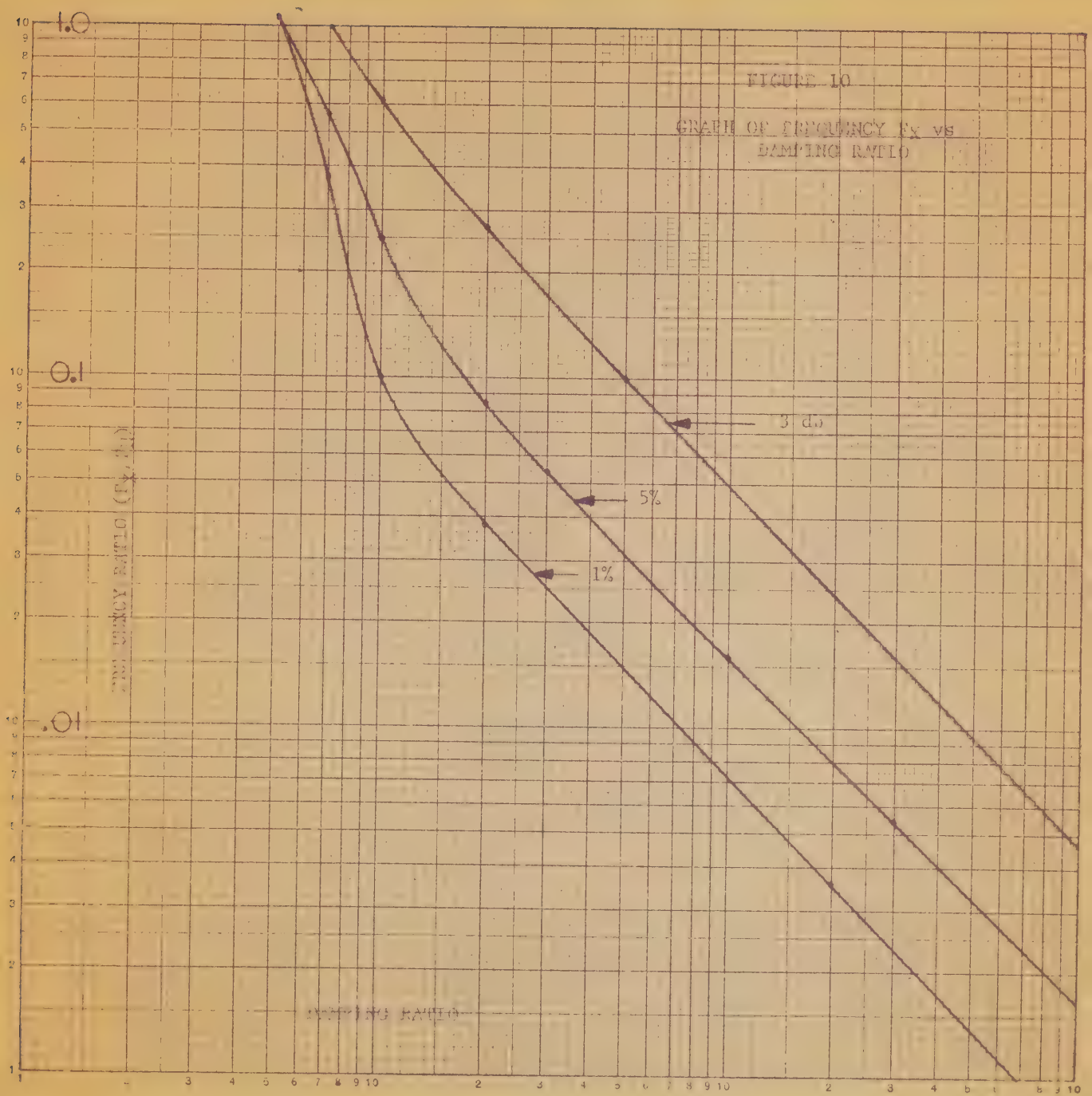


FIGURE 10
GRAPH OF FREQUENCY Fx vs
DAMPING RATIO
1.0
0.1
.01
3 db
5%
1%
DAMPING RATIO
FREQUENCY RATIO (F/Fx)

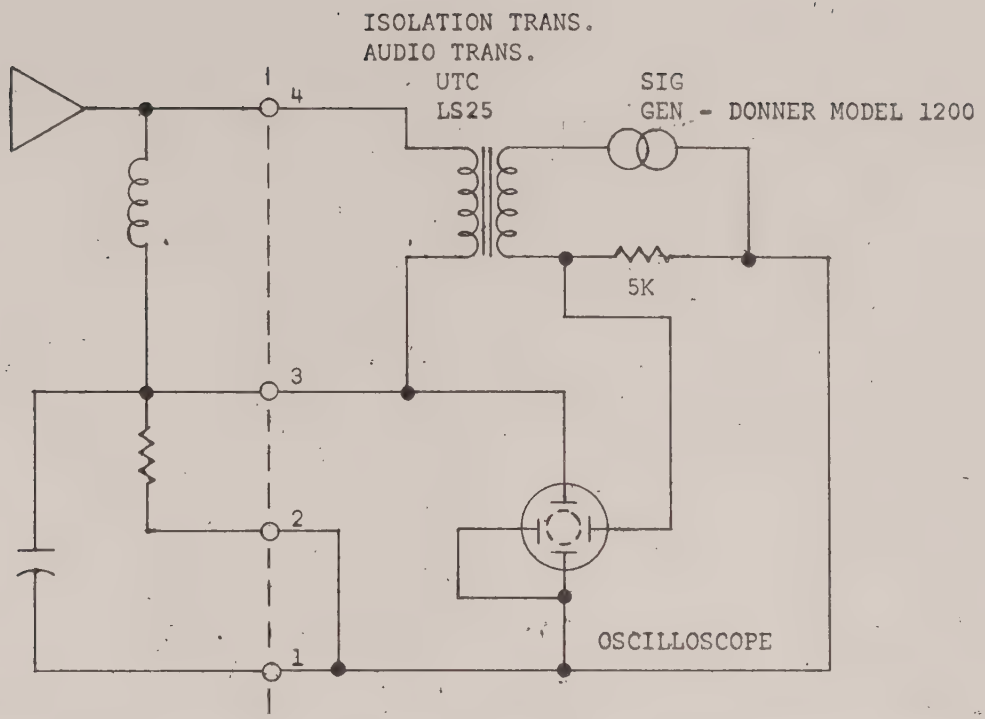


FIGURE 11. FREQUENCY RESPONSE TEST CIRCUIT (NON-OIL-FILLED INSTRUMENTS)

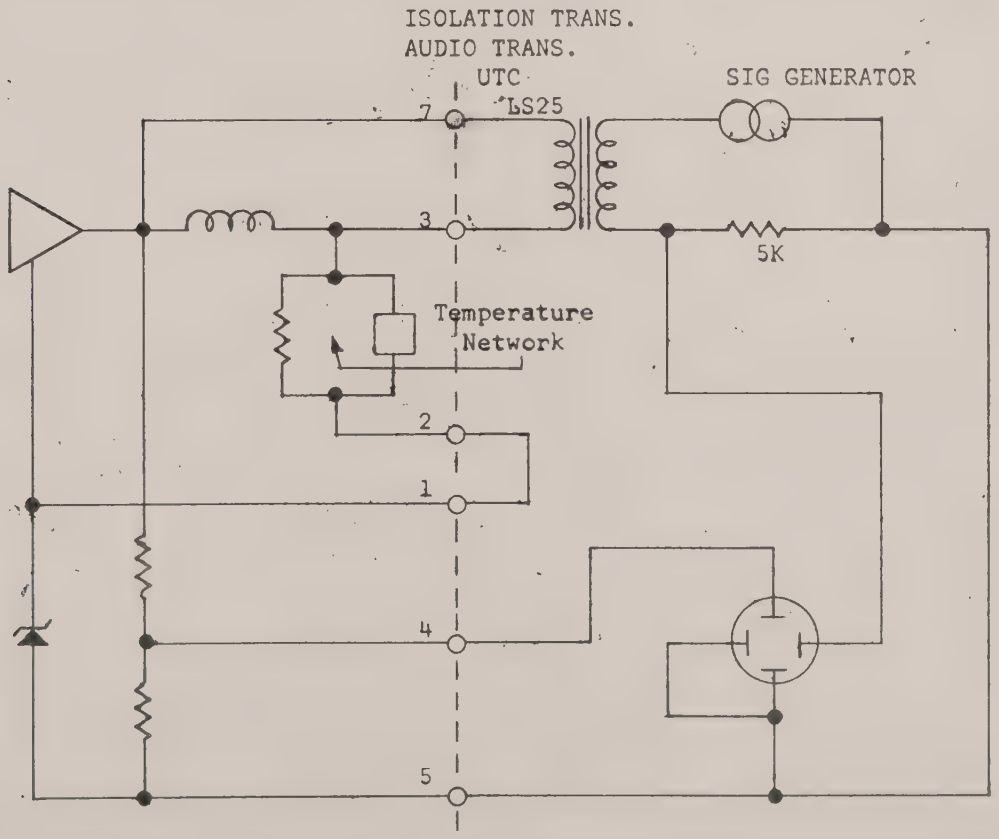


FIGURE 11 T (Telemetry) FREQUENCY RESPONSE TEST CIRCUIT (NON-OIL-FILLED INSTRUMENT

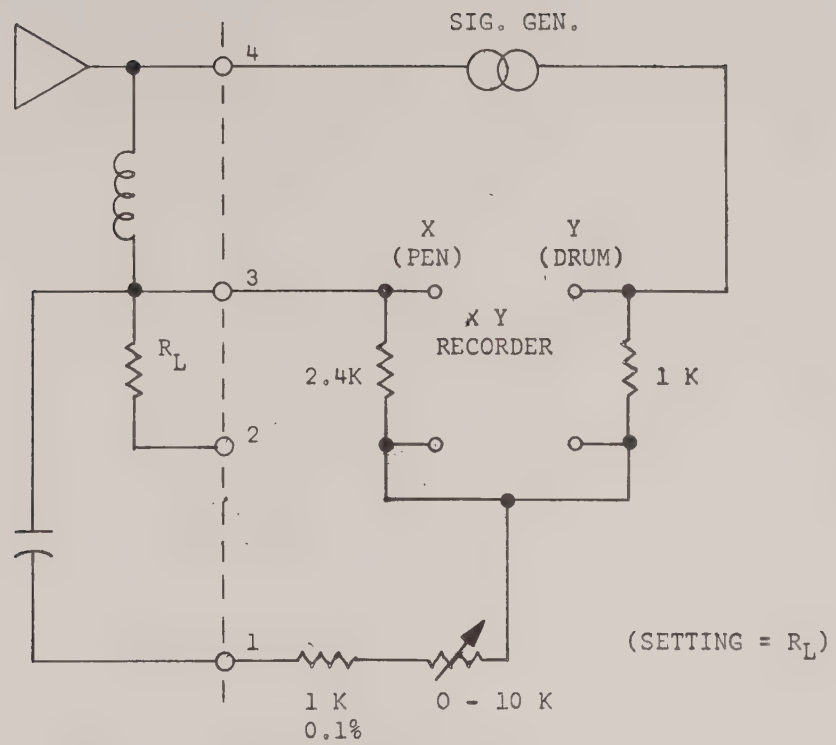


FIGURE 12. HYSTERESIS TEST CIRCUIT

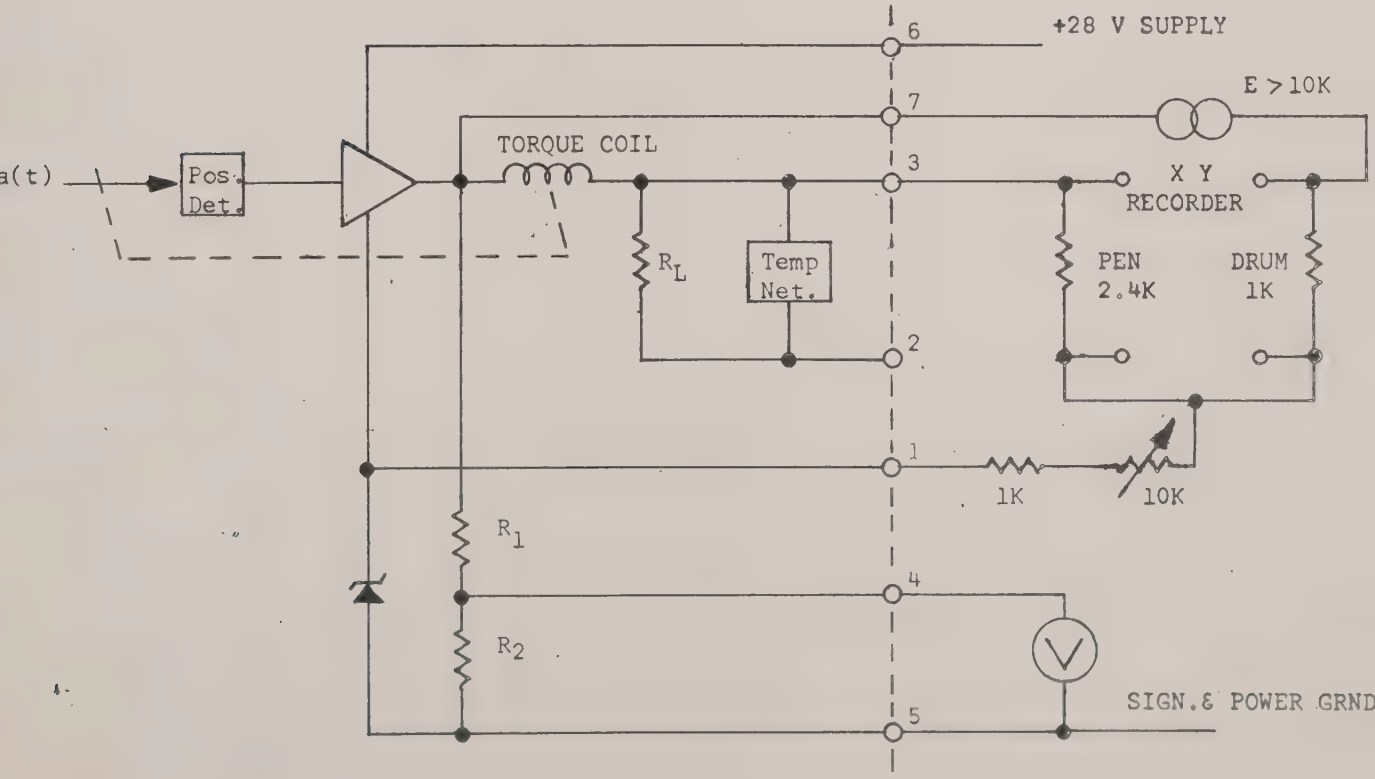


FIGURE 12 T (Telemetry) HYSTERESIS TEST CIRCUIT

A. Current Sensitivity = $\frac{0.4\ ma}{0.6G}$ = 0.7ma/G

$\frac{9.75\ ua - 2.5\ ua}{4}$ = 1.56ua

Cross-axis Sensitivity = $\frac{1.56ua}{3700ua}$ = 0.000270/G

B. % Hysteresis = $\frac{1/2 \times 2.5ua}{3700ua}$

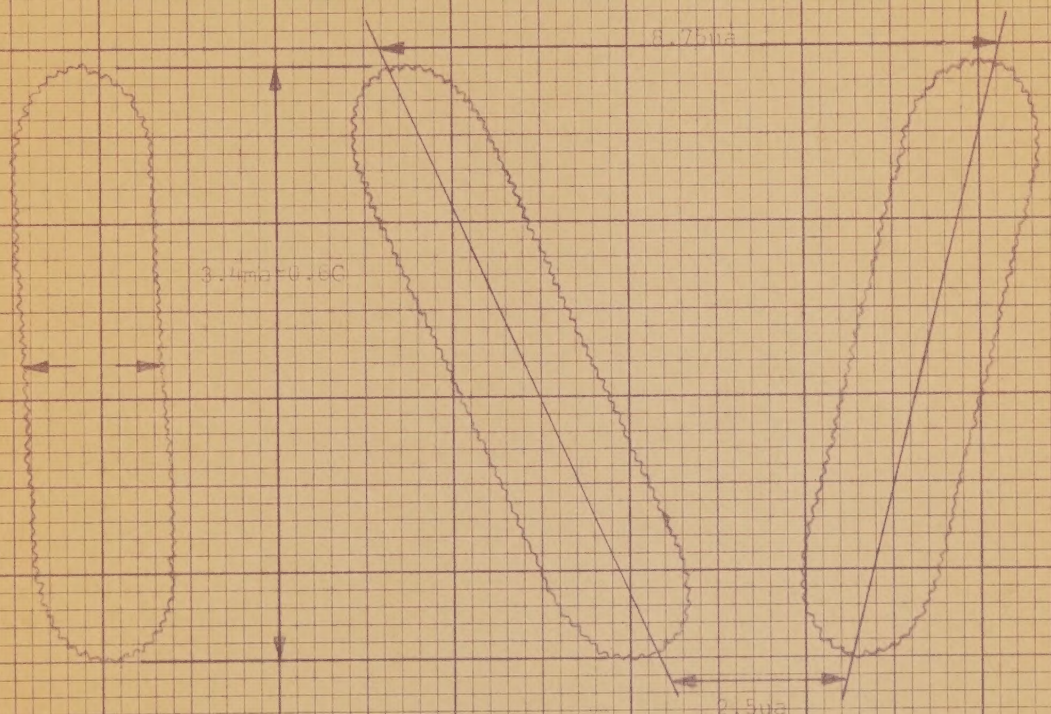


FIGURE 13

CALCULATION OF HYSTERESIS AND CROSS-AXIS SENSITIVITY

Scale: Horizontal - 1" = 2.5ua
Vertical - 1" = 1ma

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